

All data taken at the Pacific Northwest National Laboratory
FTS Operators: John S. Loring, Ashley M. Bradley and Russell G. Tonkyn
Data Analysis: Russell G. Tonkyn and Oliva M. Primera-Pedrozo

Composite spectrum for: Benzene

- First Column: Position in wavenumber (cm^{-1})
- Second column: Real refractive index $n(\tilde{\nu})$ (dispersion index)
- Third column: Imaginary refractive index, $k(\tilde{\nu})$ (absorption index per unit length in centimeters)

Where the complex refractive index $\hat{n} = n(\tilde{\nu}) + ik(\tilde{\nu})$

Following Bertie (in the references below) we define the absorbance as $A = -\log_{10}(I/I_0)$ and the linear absorption coefficient $K = A/d$, where d is the path length. The connection between the imaginary refractive index and the absorbance coefficient arises from the following: $2.303K = 4\pi\tilde{\nu}k$

See the following references for a detailed description of terms and units:

- 1) Bertie, J. E., Zhang, S. L., Eysel, H. H., Baluja, S., & Ahmed, M. K. (1993). Infrared Intensities of Liquids XI: Infrared Refractive Indices from 8000 to 2 cm^{-1} , Absolute Integrated Intensities, and Dipole Moment Derivatives of Methanol at 25°C . *Appl. Spec.*, 47(8), 1100-1114 doi:10.1366/0003702934067973
- 2) Bertie, J. E., Zhang, S. L., & Keefe, C. D. (1995). Measurement and use of absolute infrared absorption intensities of neat liquids. *Vibrational Spectroscopy*, 8(2), 215-229. doi:10.1016/0924-2031(94)00038-i

Sample:

- Chemical name, formula and CAS number: Benzene, C_6H_6 , [71-43-2]
- IUPAC name: Benzene
- Synonyms: Benzol; Phene; Phenyl hydride; Cyclohexatriene
- Physical properties: FW = 78.11 g/mole; mp = 5.5°C ; bp = $80\text{--}80.2^\circ\text{C}$; $\rho = 0.88\text{ g/cm}^3$
- Supplier and stated purity: MIR: Sigma-Aldrich, 99.8% (Lot # SHBG6315V); NIR: Sigma-Aldrich, 99.8% (Lot # SHBL0431)
- Temperature of sample: 26°C ($\pm 1^\circ\text{C}$)
- Individual samples were measured at the following path lengths: MIR: 0.64, 1.7, 2.3, 10.1, 12.9, 36.5, 91.7, 93.2, 197, 523, 1020 and $1233\text{ }\mu\text{m}$; NIR: 109, 195, 489, 2099 and $3997\text{ }\mu\text{m}$. Final data are a composite of these spectra.
- Sample cell window material is potassium bromide (KBr) except for the 2099 and $3997\text{ }\mu\text{m}$ cells which are potassium chloride (KCl).
- Preparation: None.

NIR Instrument Parameters:

- Bruker Vertex 70, purged with UHP nitrogen
- Spectral range: 10,000 to $3,000\text{ cm}^{-1}$ (1.0 to 3.33 microns)
- IR source: Quartz tungsten bulb
- Beamsplitter: Broadband Potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 31604.8 to 0 cm^{-1}

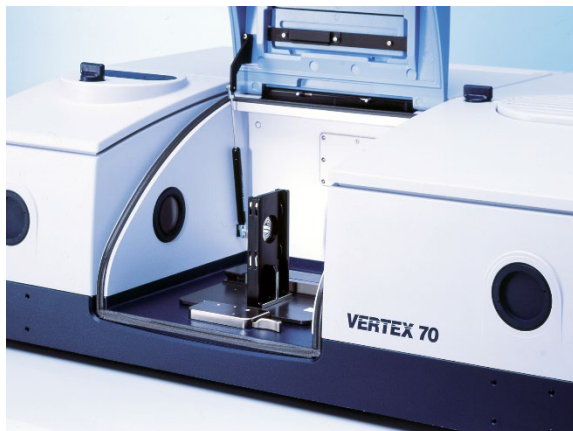
MIR Instrument Parameters:

- Tensor 27, purged with UHP nitrogen
- Spectral range: $7,800$ to 400 cm^{-1} (1.282 to 25 microns)
- NIR source: Silicon carbide glow bar
- Beamsplitter: Broadband Potassium bromide (KBr)
- Detector: DLTGS at room temperature
- Aperture: 3 mm
- Folding limits: 15802 to 0 cm^{-1}

NIR/MIR Instrument Parameters:

- Instrument resolution: 2.0 cm^{-1}
- Number of interferograms averaged per single channel spectrum: 128
- Apodization: Norton-Beer, Medium
- Phase correction: Mertz
- Scanner velocity: 10 kHz
- Interferogram zerofill: 4x
- Spectral interval after zerofilling: 0.4823 cm^{-1}

a)



b)



Figure 1: The Bruker Vertex 70 FTIR (a) and Tensor 27 FTIR (b).

Measured Refractive Index:

The refractive index for Benzene was measured at $25\text{ }^{\circ}\text{C}$ using an Atago model DR-M2/1550 Abbe refractometer. Notch filters were employed in front of a white light source to make measurements at multiple wavelengths. An infrared viewer from Atago was used to detect signal at 1550 nm . The temperature was controlled to match that in the sample compartment of the FTIR using a heated circulating bath.

480 nm: $n = 1.5106$	486 nm: $n = 1.5092$	546 nm: $n = 1.5015$
589 nm: $n = 1.4978$	644 nm: $n = 1.4941$	656 nm: $n = 1.4928$
1550 nm: $n = 1.4726$		

The refractive index, n , vs. wavelength in microns, λ , was fit to an equation similar to that of Sellmeier:

$$n(\lambda) = \{a + b/(\lambda^2 - c)\}^{1/2}$$

The resulting best-fit equation was used to find the refractive index at the highest energy data points in our experimental spectra. For Benzene the results were

$$\begin{aligned} n(7,800\text{ cm}^{-1}) &= 1.4749 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for MIR data and} \\ n(10,000\text{ cm}^{-1}) &= 1.4793 \text{ at } 25\text{ }^{\circ}\text{C} \text{ for NIR and merged data.} \end{aligned}$$

Post Processing and Related Parameters:

For the MIR, a composite spectrum was created from 12 absorbance spectra (base-10) taken at 12 path lengths: 0.6, 1.7, 2.3, 10.1, 12.9, 36.5, 91.7, 93.2, 197, 523, 1020 and 1233 micrometers (μm). For the NIR, a composite spectrum was created from 5 absorbance spectra (base-10) taken at 5 path lengths: 109, 195, 489, 2099 and 3997 μm . At each path length several spectra were measured and the results averaged for better signal to noise. The measured cell lengths were adjusted using Beer's law plots in which the NIR and MIR data were analyzed independently.

- 1) The imaginary part of the refractive index, or k vector, was determined for each absorbance file as per Bertie's program "RNJ46A" (see reference above). This takes into account the reflective losses due to the KBr and/or KCl windows.
- 2) A composite k vector is created via a classical, weighted, linear, least squares fit using the output files of program "RNJ46A": Intercept=0, slope is fitted, individual absorbance values weighted by T^2 (transmission squared), all absorbance values ≥ 2.5 are given zero weight. For the MIR, five composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 523, 1020 through 1233 μm cells. This k vector determined the final values for the range from 7800 to 4140 cm^{-1} .
 - b) The second k vector used the results from the 37 through 197 μm cells. This k vector determined the final values for the range from 4140 to 3150 cm^{-1} .
 - c) The third k vector used the results from the 0.6 through 13 μm cells. This k vector determined the final values for the range from 3150 to 2950 cm^{-1} , 1660 to 1400 cm^{-1} and 750 to 560 cm^{-1} .
 - d) The fourth k vector used the results from the 13 through 197 μm cells. This k vector determined the final values for the range from 2950 to 1600, 1400 to 1100 and 560 to 400 cm^{-1} .
 - e) The fifth k vector used the results from the 2.3 through 37 μm cells. This k vector determined the final values for the range from 1100 to 750 cm^{-1} .
- 3) A frequency correction was applied to the resulting composite MIR k vector.
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.99975 + 0.003891]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 4) For the NIR, five composite vectors were created and merged by hand.
 - a) The first k vector used the results from the 2099 and 3997 μm cells. This k vector determined the final values for the range from 10000 to 6400 cm^{-1} .
 - b) The second k vector used the results from the 109 through 2099 μm cells. This k vector determined the final values for the range from 6400 to 5800 cm^{-1} .
 - c) The third k vector used the results from the 489 through 3997 μm cells. This k vector determined the final values for the range from 5800 to 4800 cm^{-1} .
 - d) The fourth k vector used the results from the 109 and 195 μm cells. This k vector determined the final values for the range from 4800 to 3400 cm^{-1} .
 - e) The fifth k vector used the results from the 109, 489 and 2099 μm cells. This k vector determined the final values for the range from 3400 to 3100 cm^{-1} .
- 5) The resulting composite NIR k vector and the refractive index at 10,000 cm^{-1} were used to create the real or n vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."
 - a) Frequency correction (already applied): $\tilde{\nu}(\text{corrected}) = [\tilde{\nu}(\text{instrument}) * 0.999748 + 0.00481475]$ as determined by comparing measured atmospheric spectral lines (H_2O and CO_2) to values from the Northwest Infrared Spectral Library Database.
- 6) Finally, the MIR data were mapped onto the NIR x-axis using an interpolation routine, i.e. the Make Compatible command in OPUS 5.5. Then the composite MIR and NIR k vectors were merged to generate a final composite k vector across the entire spectral range. The NIR data were used exclusively above 4500 cm^{-1} , and only the MIR data were used below 4400 cm^{-1} . A weighted average, with the weight of the MIR vector increasing linearly from 0 to 100% between 4500 and 4400 cm^{-1} was used in the overlapping spectral region. The resulting composite k vector and the refractive index at 10,000 cm^{-1} were used to create the final n vector using the Kramers-Kronig relation, as per Bertie's program "LZZKTB."

Photographs of Sample Benzene:

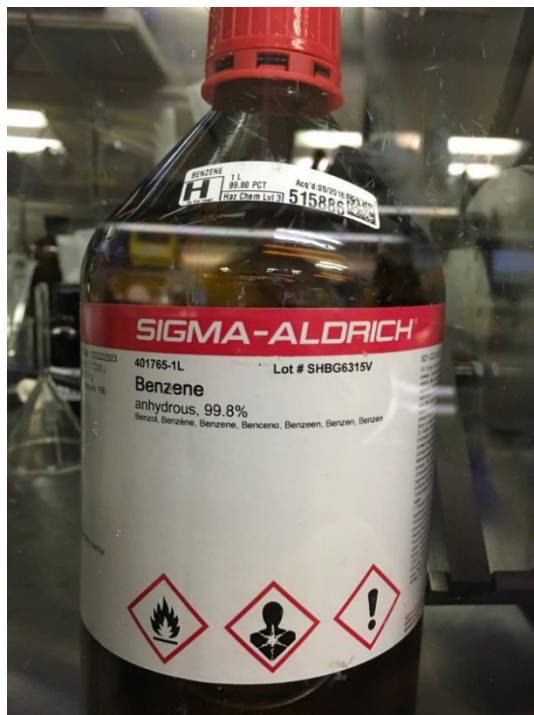


Figure 2: Benzene in Sigma-Aldrich container for MIR measurements.



Figure 3: Benzene in Sigma-Aldrich container for NIR measurements.